

# Hypernuclear physics legacy and heritage of Dick Dalitz<sup>\*</sup>

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## Abstract

The major contributions of Richard H. Dalitz to hypernuclear physics, since his first paper in 1955 to his last one in 2005 covering a span of 50 years during which he founded and led the theoretical study of hypernuclei, are reviewed from a personal perspective. Topical remarks on the search for quasi-bound  $\bar{K}$ -nuclear states and on kaon condensation are made.

*Key words:* biographies; history of science; hypernuclei;  $K^-$  deeply bound states

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## 1 Introduction

Dick Dalitz was born in Dimboola, in the state of Victoria, Australia, on February 28th 1925, and gained B.A. and B.Sc. degrees in Mathematics and Physics in 1944 and 1945, respectively, from the University of Melbourne. He moved to Britain in 1946 for postgraduate studies at Cambridge, and then worked at the University of Bristol before joining in 1949 Rudolf Peierls in Birmingham. There he completed and wrote up his Ph.D. thesis on ‘ $0^+ \rightarrow 0^+$  transitions in nuclei’, supervised by Nicholas Kemmer of Cambridge, and subsequently became a Lecturer. He spent two years in the U.S. from 1953, holding research positions at Cornell and Stanford, visiting also Princeton and Brookhaven National Laboratory, and returned as a Reader in Mathematical Physics to the

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University of Birmingham for a year before becoming Professor of Physics in the Enrico Fermi Institute for Nuclear Studies and the Department of Physics at the University of Chicago in 1956. He moved to Oxford in 1963 as a Royal Society Research Professor, the post he held until his retirement in 1990. In addition to the Dalitz Plot, Dalitz Pair and the Castillejo-Dalitz-Dyson (CDD) Pole that bear his name, he pioneered the theoretical study of strange baryon resonances, of baryon spectroscopy in the quark model, and of hypernuclei, to all of which he made outstanding contributions. His formulation of the  $\theta - \tau$  puzzle led to the discovery that parity is not a symmetry of the weak interactions. A complete bibliography of Dalitz's works is available in Ref. [1].

During his postgraduate studies he spent a year working alongside Cecil Powell's cosmic ray group at Bristol and it was during this period that he took particular interest in the strange particles that were beginning to appear in cosmic rays and at particle accelerators. These included the first hyperfragment in 1952 [2] which inspired a lifelong interest in hypernuclei. Later on, he made significant contributions to the strong interactions of the strange particles and their resonant states [3,4]. As early as 1959 Dalitz and Tuan, by analysing the data on the strong interactions of  $K^-$  mesons with protons, predicted the existence of an  $I = 0$ ,  $J^\pi = (1/2)^-$  strange resonance about 20 MeV below the  $K^- p$  threshold [5]. This  $\Lambda(1405)$  resonance was discovered two years later in the Berkeley hydrogen bubble chamber, studying the reaction  $K^- p \rightarrow \Sigma + 3\pi$  for several charge states [6]. The proximity of this  $s$ -wave  $\pi\Sigma$  resonance to the  $\bar{K}N$  threshold suggested that it can be generated by  $\bar{K}N - \pi\Sigma$  inter-hadron forces, and this was shown in 1967 by Dalitz to be possible within a dynamical model of SU(3)-octet vector-meson exchange [7] which is, in fact, the underlying physical mechanism for the Tomozawa-Weinberg leading term in the chiral expansion of the meson-baryon Lagrangian [8,9]. The vector mesons  $\rho, \omega, K^*, \phi$ , which were discovered in the years 1960-62, relying heavily on Dalitz plots for some of these, were unknown when the  $\Lambda(1405)$  was predicted. In the years to follow, Dalitz repeatedly considered the completeness of this dynamical picture, whether or not the  $S$ -matrix pole of  $\Lambda(1405)$  due to the inter-hadron forces need not be augmented by a CDD pole arising from inter-quark forces upon allowing for an intermediate  $uds$  configuration. It is here that the earlier CDD discussion [10] found a fertile physical ground.

Looking back years later at the development of his own career, he made the following remarks [11] (which he rarely allowed himself to make in public):

- Yes, as Gell-Mann said, pion physics was indeed the central topic for theoretical physics in the mid 1950s, and that was what the young theoretician was expected to work on. The strange particles were considered generally to be an obscure and uncertain area of phenomena, as some kind of dirt effect which could not have much role to play in the nuclear forces, whose

*comprehension was considered to be the purpose of our research. Gell-Mann remarked that he spent the major part of his effort on pion physics in that period, and I did the same, although with much less success, of course.*

- *Fashions have always been strong in theoretical physics, and that holds true today as much as ever. The young physicist who is not working on those problems considered central and promising at the time, is at a disadvantage when he seeks a post. This tendency stems from human nature, of course, but it is unfortunate, I think, that the system operates in such a way as to discourage the young physicist from following an independent line of thought.*

Although about 30% of his research papers were devoted or connected to hypernuclei, Dalitz was primarily a particle physicist. This is reflected in the interview he gave during HYP03 [12], where hypernuclei get only the following two brief remarks:

- *My interest in hypernuclear events developed particularly well in Chicago because a young emulsion experimenter, Riccardo Levi-Setti, whose work I had known from his hypernuclear studies in Milan, came to the Institute for Nuclear Studies at this time. We each benefited from the other, I think, and we got quite a lot done.*
- *I was responsible for organizing particle-physics theory in Oxford. Besides quark-model work, I still did work on hypernuclear physics, much of this with Avraham Gal of Jerusalem.*

I first met Dalitz as a young student attending the 1966 Varenna International School of Physics “Enrico Fermi”, Course XXXVIII on ‘Interaction of High-Energy Particles with Nuclei’. He gave a series of lectures on the status of Hypernuclear Physics, and I was lucky to have been able to intercept him during one of the lectures, apprising him of an important omission he had made in a calculation of transition matrix elements with which I was familiar owing to my shell-model education at the Weizmann Institute. This was the beginning of a very close collaboration lasting about 20 years during which we would often meet for joint periods of work, always discussing the latest experimental results and their likely interpretations. I have been amazed at Dalitz’s encyclopaedic knowledge and mastery of measurements and calculations in particle physics and also of many aspects of nuclear physics, his critical assessment of experimental results and his thoroughness at work. He always insisted on and managed to calculate things in his own way, relying only on facts, never on fancy. Our ways somewhat diverged after 1985, but we still maintained a close relationship until very recently, when I edited his last publication, the talk he gave at HYP03 [13].

## 2 $\Lambda$ hypernuclei

### 2.1 The beginning

Dalitz pioneered the theoretical study of hypernuclei. His first published work on  $\Lambda$  hypernuclei dates back to 1955, titled *Charge independence in light hyperfragments* [14]. It focused on the near equality of the ( $^4_{\Lambda}\text{H}$ ,  $^4_{\Lambda}\text{He}$ ) binding energies and its origin in the charge symmetry of the  $\Lambda N$  interaction, and on the exceedingly small binding energy of  $^3_{\Lambda}\text{H}$ , the only bound  $A = 3$  hypernucleus marking the onset of  $\Lambda$ -hypernuclear binding. By 1959 his analyses of the light,  $s$ -shell hyperfragments led him to state [15] that *the existence of a bound  $\Lambda$ -nucleon system is strongly excluded* and that *the analysis of the  $T = 1$  triplet  $^3_{\Lambda}\text{He}$ ,  $^3_{\Lambda}\text{H}$ ,  $^3_{\Lambda}\text{n}$  indicates that these systems are not expected to form bound states*, and that these essential conclusions *would not be seriously affected if there exist moderately strong three-body forces arising from pion exchange processes*. He returned in 1972 to consider the possible effects of three-body  $\Lambda NN$  forces in the  $s$  shell [16] quantifying what has been since called ‘the overbinding problem’, namely that the binding energy of  $^5_{\Lambda}\text{He}$  comes out too large by 2–3 MeV in any calculation that fits well the binding energies of the lighter hypernuclei.<sup>1</sup>

In a series of works covering three decades, he used the main  $\Lambda \rightarrow p\pi^-$  weak-decay mode of light hypernuclear species studied in emulsion and bubble chambers to determine their ground-state spins and, thereby, to gain information on the spin dependence of the  $\Lambda N$  force. When he had begun this line of works, just before parity violation was realised during the turbulent 1956–1957 period, he wrongly concluded in a talk given at the 6th Annual Rochester Conference on High Energy Nuclear Physics in April 1956 that the triplet  $\Lambda N$   $s$ -wave interaction was stronger than the singlet one [17]. His argument was based on assuming that parity was respected in the weak decay  $^4_{\Lambda}\text{H} \rightarrow \pi^- + ^4\text{He}$ . Since the final products all had spin zero, and the pion was known to have a negative intrinsic parity with respect to nucleons, (quoting Dalitz, in *italics*) *the spin-parity possibilities for the ( $^4_{\Lambda}\text{H}$ ,  $^4_{\Lambda}\text{He}$ ) doublet are  $0^-$ ,  $1^+$ ,  $2^-$ , etc.* Assuming (at that time it was still uncertain) that the  $\Lambda$  hyperon had spin-parity  $(1/2)^+$ , the spin-parity of  $^4_{\Lambda}\text{H}$  had to be  $1^+$ , and this meant that the triplet  $\Lambda N$   $s$ -wave interaction was stronger than the singlet one, and *one also concludes that the spin-parity for  $^3_{\Lambda}\text{H}$  is  $(3/2)^+$ .* Of course we now know that this was wrong; and indeed soon after Dalitz himself, realising the merits of the strong spin selectivity provided by parity violation in the weak-interaction pionic decays of  $\Lambda$  hypernuclei, calculated the branching ratios of the  $\pi^-$  two-body decays

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<sup>1</sup> we now know that it need not be the case once  $\Lambda N - \Sigma N$  coupling is explicitly allowed in.

of  ${}^4_{\Lambda}\text{H}$  and  ${}^3_{\Lambda}\text{H}$  to the daughter ground states of  ${}^4\text{He}$  and  ${}^3\text{He}$ , respectively, in order to determine unambiguously the ground-state spins of the parent hypernuclei [18] which in a few years became experimentally established as  $0^+$  [19] and  $(1/2)^+$  [20] respectively. This led to the correct ordering of the triplet and singlet  $\Lambda N$   $s$ -wave interactions as we understand it to date.

Dalitz's outstanding contribution in the 1960s to weak interactions in hypernuclei, together with Martin Block [21], was to formulate the  $\Lambda N \rightarrow NN$  phenomenology of non-mesonic weak-interaction decay modes that dominate the decays of medium-weight and heavy hypernuclei, a process that cannot be studied on free baryons and which offers new systems,  $\Lambda$  hypernuclei, for exploring the little understood  $\Delta I = 1/2$  rule in non-leptonic weak interactions. The state of the art in understanding non-mesonic weak decay in  $\Lambda$  hypernuclei is reviewed in this Issue, experimentally by H. Outa and theoretically by G. Garbarino. This chapter in hypernuclear physics is still incomplete, and more experimentation is needed before the underlying physics is fully uncovered.

## 2.2 The later years

Dalitz's work on the  $p$ -shell hypernuclei, dates back to 1963 when together with Levi Setti, in their only joint paper [22], *Some possibilities for unusual light hypernuclei* were discussed, notably the neutron-rich isotopes of  ${}^6_{\Lambda}\text{H}$  and  ${}^8_{\Lambda}\text{He}$  belonging to  $I = 3/2$  multiplets, but his systematic research of the  $p$ -shell hypernuclei started in 1967 together with me laying the foundations for a shell-model analysis of  $\Lambda$  hypernuclei [23]. Using these shell-model techniques, subsequently we were able to chart the production and  $\gamma$ -ray decay schemes anticipated for excited states in light  $\Lambda$  hypernuclei in order to derive the complete spin dependence of the  $\Lambda N$  interaction effective in these hypernuclei [24]. This work was further developed together with John Millener and Carl Dover [25], serving as a useful guide to the hypernuclear  $\gamma$ -ray measurements completed in the last few years, at BNL and at KEK [26], which yielded full determination of the spin dependence in the low-lying spectrum (contributions by H. Tamura and by D.J. Millener, in this Issue).

As early as 1969 data on excited states were reported with the  $\Lambda$  hyperon in a  $(1p)_{\Lambda}$  state coupled to the nuclear ground-state configuration, first from emulsion data [27,28] observing proton decay in some special instances such as  ${}^{12}_{\Lambda}\text{C}$ , and later on through in-flight ( $K^-, \pi^-$ ) experiments at CERN and BNL. In the particular case of the  ${}^{12}_{\Lambda}\text{C}$  excited cluster of states about 11 MeV above the  $(1s)_{\Lambda}$  ground state, Dalitz participated actively in the first round of theoretical analysis for both types of experiments [29,30]. However, confronting these and similar data posed two difficulties which we identified and discussed

during 1976. The first one was connected to understanding the nature of the  $\Lambda$  continuum spectrum which, owing to the small momentum transfer in the forward-direction ( $K^-, \pi^-$ ) reaction in flight, was thought to consist of well defined  $\Lambda$ -hypernuclear excitations. It was not immediately recognised that since the  $\Lambda$  hyperon did not have to obey the Pauli exclusion principle with nucleons, hypernuclear quasi-free excitation was possible even at extremely small values of the momentum transfer, a possibility that was pointed out and analysed quantitatively by us [31] following the first round of data taken by the Heidelberg-Saclay collaboration at the CERN-PS in 1975.

The other difficulty was connected with understanding the role of coherent excitations in the  $(1p)_\Lambda$  continuum, the so called ‘substitutional’ or ‘analogue’ states, where the early theoretical concept of analogue states stemmed from considerations of octet-SU(3) unitary symmetry. Already in his first discussion of these states in 1969 [32], Dalitz recognised *that the strong excitation of these states does not depend on SU(3) symmetry. In fact it is reasonable to believe that SU(3) symmetry has almost no relevance to the relationship between  $\Lambda$ -hypernuclei and nuclei...simply because the mass difference of 80 MeV between the  $\Lambda$  and  $\Sigma$  hyperons...is a very large energy relative to the typical energies associated with nuclear excitations.* This difficulty was eliminated by Kerman and Lipkin [33] who suggested in 1971 to consider the Sakata triplet-SU(3) unitary symmetry version in which the proton, neutron and  $\Lambda$  were degenerate. This suggestion was further limited by us in 1976 to  $(1p)_{p,n,\Lambda}$  states and, together with Pauli-spin SU(2) symmetry, led to the consideration of Pauli-Sakata SU(6) supermultiplets encompassing nuclei and hypernuclei [34], in direct generalisation of Wigner’s supermultiplet theory of spin-isospin SU(4) symmetry in light nuclei. The analysis of these SU(6) supermultiplets proved very useful for the development of shell model techniques in the 1980s and on by John Millener and collaborators [35]. In particular, the 1976 work focused on the concept of the ‘supersymmetric’ state in addition to the ‘analogue’ state, with the low-lying supersymmetric state arising from the non existence of a Pauli exclusion principle between the  $\Lambda$  hyperon and nucleons.

### 3 $\Lambda\Lambda$ hypernuclei

Dalitz in fact anticipated that  $\Lambda\Lambda$  hypernuclei be observed and that as a rule they would be particle stable with respect to the strong interaction. His Letter titled *The  $\Lambda\Lambda$ -hypernucleus and the  $\Lambda - \Lambda$  interaction* [36] appeared as soon as the news of the first observed  $\Lambda\Lambda$ -hypernucleus  $^{10}_{\Lambda\Lambda}\text{Be}$  was reported in 1963 [37] and was followed by a regular paper [38]. He did not work on  $\Lambda\Lambda$  hypernuclei for a long period, until 1989, apparently because there were no new experimental developments in this field except for the  $^6_{\Lambda\Lambda}\text{He}$  dubious event reported by Prowse in 1966. He returned to this subject in 1989 [39]

feeling the need to scrutinize carefully the interpretation of the  $^{10}_{\Lambda\Lambda}$ Be event and its implications in view of a renewed experimental interest to search for the  $H$ -dibaryon. This scientific chapter in Dalitz's life is described in Don Davis' companion contribution in this Issue.

#### 4 $\Sigma$ hypernuclei

Dalitz was puzzled by the CERN-PS low-statistics evidence in the beginning of the 1980, and subsequently by the KEK-PS low-statistics evidence in 1985, for relatively narrow  $\Sigma$ -hypernuclear peaks in the continuum. The large  $\Sigma N \rightarrow \Lambda N$  low-energy cross section, due primarily to the strong pion exchange potential, did not leave much room for narrow  $\Sigma$  states in nuclei; indeed, the first rough estimate by Gal and Dover [40] gave nuclear-matter widths of order  $\Gamma_\Sigma \sim 25$  MeV. The suggestion by these authors that some  $\Sigma$ -hypernuclear levels could selectively become fairly narrow due to the  $S = 1$ ,  $I = 1/2$  dominance of the  $\Sigma N \rightarrow \Lambda N$  transition fascinated him to the extent that he argued favorably for the validity of this interpretation in his 1980 Nature article *Discrete  $\Sigma$ -hypernuclear states* [41], although taking it with a grain of salt. He came back to this subject in 1989, after hearing in HYP88 at Padova Hayano's report of the KEK  $K_{\text{stop}}^-$  experiment [42] finding evidence for a  $^4\Sigma$ He near-threshold narrow state. Recalling some old bubble-chamber data on  $K_{\text{stop}}^-$  absorption yields in  $^4\text{He}$  near the  $\Sigma$  threshold, he questioned together with Davis and Deloff [43] the compatibility of assigning this  $^4\Sigma$ He as a quasi-bound state with the older data: *Is there a bound  $^4\Sigma$ He?* He came back to these questions with Deloff in both HYP91 in Shimoda [44] and HYP94 in Vancouver [45], but as soon as this same  $^4\Sigma$ He structure was observed in a  $(K^-, \pi^-)$  in-flight experiment at the BNL-AGS accelerator [46], and the measured pion spectrum was explained satisfactorily within a comprehensive DWIA calculation [47] in terms of a  $^4\Sigma$ He quasi-bound state, he openly during HYP00 [48] and HYP03 [13] removed his objections.

#### 5 Exotic structures

I have already mentioned that Dalitz was far from jumping on band wagons of speculative ideas unless there were some good experimental or phenomenological tests to be made in a concrete manner. A notable exception is a Nature paper coauthored by Dalitz, *Growing drops of strange matter* [49], discussing a possible scenario for getting into strange quark matter. It is therefore timely to wonder how Dalitz would have reacted to the flood of recent reports on the possible existence of  $\bar{K}$ -nuclear bound states and on the ongoing experimental

searches for such objects, particularly since the prototype of such states, the  $\Lambda(1405)$ , was first interpreted and calculated in a paper led by him [7] as an unstable  $\bar{K}N$  bound state.

### 5.1 $\bar{K}$ -nuclear bound states?

The state of the art in searches for  $\bar{K}$ -nuclear bound states is reviewed in this Issue by M. Iwasaki for the KEK experiments, stopping  $K^-$  mesons on a  ${}^4\text{He}$  target, and by A. Filippi for the FINUDA spectrometer collaboration in Frascati, stopping  $K^-$  mesons on several targets, including isotopes of Li and  ${}^{12}\text{C}$ . At the background of these stopped  $K^-$  experiments was the prediction of a particularly narrow and deeply bound  $I = 0$   $\bar{K}NNN$  tribaryon, and the related estimate given by Akaishi and Yamazaki for its production rate  $\sim 2\%$  per stopped  $K^-$  in  ${}^4\text{He}$  [50]. This estimate is totally unacceptable since a production rate of this order of magnitude is known to hold at rest for (the most favourable)  $A = 4$  hypernuclei [51]; hypernuclei are produced via the dominant absorptive  $K^-N \rightarrow \pi Y$  modes, whereas the  $K^-N \rightarrow N\bar{K}$  backward-elastic mode responsible for replacing a bound nucleon by a bound  $\bar{K}$  is suppressed at rest with respect to the former reactive modes owing to the  $1/v$  law near threshold. Realistic estimates give rates as low as  $10^{-4}$  per stopped  $K^-$  for the production of  $\bar{K}$ -nuclear bound states [52]. Indeed, an upper limit of order  $10^{-3}$  per stopped  $K^-$  for producing narrow  $\bar{K}NNN$  deeply bound states has been determined recently by the KEK-E549 collaboration from the observed  $(K_{\text{stop}}^-, p)$  spectrum in  $K^-$  absorption on  ${}^4\text{He}$  [53]. In-flight  $K^-$  reactions are more promising, but unfortunately will not be feasible before J-PARC is operated, from 2009 on. Preliminary  $(K^-, p)$  and  $(K^-, n)$  spectra at  $p_{\text{lab}} = 1 \text{ GeV}/c$  on  ${}^{12}\text{C}$  obtained in KEK-E548 show only appreciable strength in the  $\bar{K}$  bound-state region, but no peaks [54], in accordance with recent in-flight reaction calculations (Ref. [55]; T. Koike and T. Harada, in this Issue). Given this situation, the measurement of more exclusive spectra, and using proton or antiproton beams, or nucleus-nucleus collisions, has been advocated (P. Kienle, in this Issue).

Among the many reactions and spectra presented and discussed recently, I would like to propose interpretation to a class of very intriguing spectra that naively would be interpreted as due to an extremely deep  $K^-pp$  bound state. Preliminary results from the FOPI collaboration at GSI are shown in Fig. 1, where the  $\Lambda p$  invariant mass in both Ni+Ni and Al+Al collisions peaks at  $M_{\text{inv}}(\Lambda p) = 2.13 \pm 0.02 \text{ GeV}$ , near the  $\Sigma N$  threshold, with an appreciable width. This value of  $M_{\text{inv}}(\Lambda p)$  is substantially lower, by over 100 MeV, than the  $M_{\text{inv}}(\Lambda p)$  value assigned by the FINUDA spectrometer collaboration [57] as due to a  $K^-pp$  bound state. The possibility of a resonance or cusp phenomenon for the  $\Lambda p$  system, at or near the opening of the  $\Sigma N$  threshold, which has been

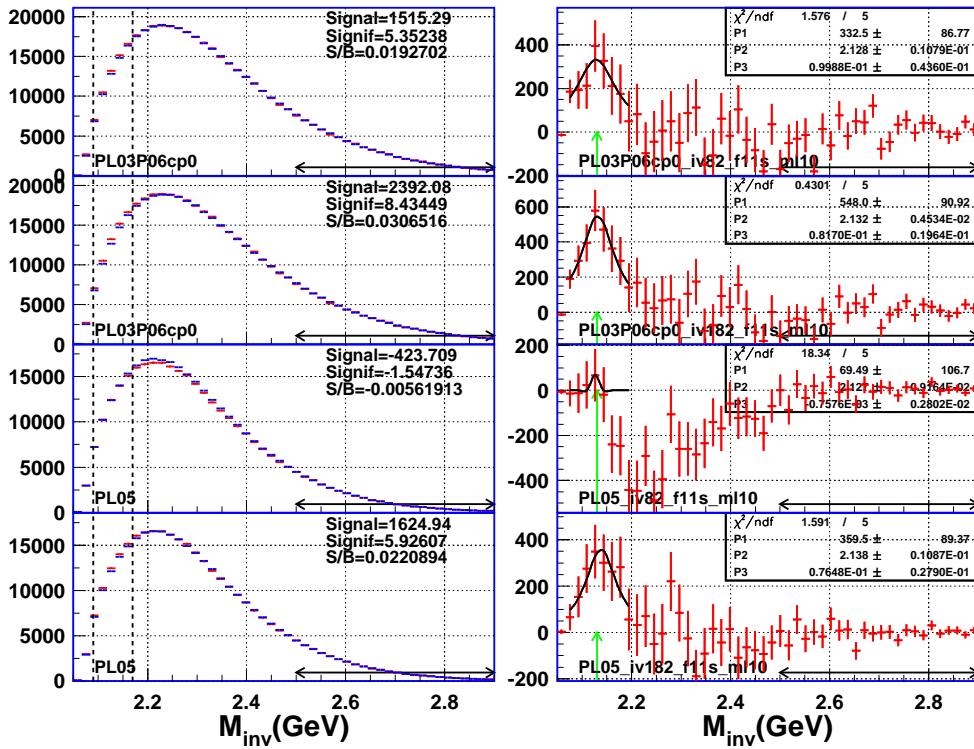


Fig. 1.  $\Lambda p$  invariant-mass spectra taken by the FOPI detector collaboration at GSI in Ni+Ni (two upper panels) and in Al+Al (two lower panels) collisions. The right-hand side panels follow alignment of the reaction plane (upper panel in each group) or alignment of the  $\Lambda$  direction (lower panel in each group). Figure provided by Norbert Herrmann and shown by Paul Kienle at HYP06 and in his contribution to this Issue [56]. I am indebted to both of them for bringing these data to my attention and for instructive discussions.

suggested in several old experiments [58,59], has always intrigued Dalitz who together with others considered it within  $K^-d$  calculations [60,61], in parallel to the Faddeev calculations done by my Ph.D. student Gregory Toker [62]. However, I dare say that had he been with us today, he would have considered favourably another possibility, that the light, only  $\Sigma$  hypernucleus known to be bound,  ${}^4_\Sigma\text{He}$  is the source of these  $\Lambda p$  pairs. The binding energy of  ${}^4_\Sigma\text{He}$  with respect to the  $\Sigma^+ + {}^3\text{H}$  threshold is  $B = 4.4 \pm 0.3(\text{stat}) \pm 1(\text{syst})$  MeV, and the value of width assigned to it is  $\Gamma = 7.0 \pm 0.7 + 1.2$  MeV [46]. Its quantum numbers are  $I = 1/2$ ,  $J^\pi = 0^+$  [47] with all four baryons in  $s$  states. In particular, it may be viewed in isospace as a linear combination of  $\Sigma^+$  coupled to  ${}^3\text{H}$  and  $\Sigma^0$  coupled to  ${}^3\text{He}$ . Its wavefunction is schematically given by:

$$\Psi({}^4_\Sigma\text{He}) = \alpha(\Sigma N)_{I=1/2,3/2}^{S=0}(NN)_{I=1}^{S=0} + \beta(\Sigma N)_{I=1/2}^{S=1}(NN)_{I=0}^{S=1}, \quad (1)$$

Table 1

Binding energies ( $B$ ) and widths ( $\Gamma$ ) calculated for  $K^-pp$  (in MeV) exclusive of  $\bar{K}NN \rightarrow YN$  contributions

	single channel		coupled channels		experiment
	ATMS [65]	AMD [66]	Faddeev [67]	Faddeev [68]	FINUDA [57]
$B$	48	16–22	50–70	60–95	$115 \pm 6 \pm 4$
$\Gamma$	61	40–70	90–110	45–80	$67 \pm 14 \pm 3$

where only the spin-isospin structure is specified. In the absence of dynamical correlations, spin and isospin considerations yield values  $\alpha^2 = \beta^2 = 1/2$ . The decay of  ${}^4\Sigma$ He is dominated by the  $(\Sigma N \rightarrow \Lambda N)_{I=1/2}^{S=1}$  two-body transition, proceeding therefore through the component with amplitude  $\beta$  in which the  $NN$  composition is  $pn$ . This means that the  $\Sigma N$  composition is a mixture of  $\Sigma^+n$  and  $\Sigma^0p$ , both of which decay to  $\Lambda p$ . One expects then  ${}^4\Sigma$ He to decay dominantly by emitting back-to-back  $\Lambda p$  pairs with slower ‘spectator’ proton and neutron which will somewhat distort the  $\Sigma N \rightarrow \Lambda p$  two-body kinematics. A more conclusive proof for this suggestion would come from the observation of back-to-back  $\Lambda^3$ He pairs in the two-body decay  ${}^4\Sigma$ He  $\rightarrow \Lambda + {}^3$ He. The branching ratio for this decay relative to the inclusive  $\Lambda X$  decay rate is perhaps a few percent, as may be argued by analogy with the approximately 8%(5%) branching ratio measured for the nonmesonic decay  ${}^4\Lambda$ He( ${}^5\Lambda$ He)  $\rightarrow n + {}^3$ He( ${}^4$ He) relative to the inclusive  $\pi^-$  decay rate of  ${}^4\Lambda$ He( ${}^5\Lambda$ He) [63,64]. Irrespective of whether or not the above conjecture of  ${}^4\Sigma$ He production is correct for the FOPI-Detector GSI experiments, it would be a wise practice for  $\bar{K}$ -nuclear bound state searches in heavy ion collisions to look first for known hypernuclear signals in order to determine their production rates as calibration and normalization standards.

## 5.2 From $K^-pp$ to kaon condensation?

Of special interest is the lightest  $\bar{K}$ -nucleus  $K^-pp$ . The FINUDA spectrometer collaboration claimed evidence for a broad  $K^-pp$  bound state, with binding energy of about 115 MeV, by observing back-to-back  $\Lambda p$  pairs from the decay  $K^-pp \rightarrow \Lambda p$  in  $K^-_{\text{stop}}$  reactions on Li and  ${}^{12}\text{C}$  (Ref. [57]; A. Filippi, in this Issue). However, these pairs could naturally arise from absorption reactions at rest when final-state interaction is accounted for (A. Ramos, in this Issue). Irrespective of whether or not the FINUDA event corresponds to a  $K^-pp$  bound state, a variety of few-body calculations as summarized in Table 1 agree that  $K^-pp$  should possess a broad state bound by less than 100 MeV. Here,  $K^-pp$  stands loosely for the projection onto the  $S = 0$ ,  $I = 1/2$ ,  $I_z = 1/2$   $s$ -wave component of  $\bar{K}NN$ . Its charge symmetric state, with  $I_z = -1/2$ , is  $\bar{K}^0nn$ . The table demonstrates that  $\bar{K}$  mesons can bind nuclear clusters that are otherwise unbound. The point here is that the underlying  $K^-p$  and  $\bar{K}^0n$  in-

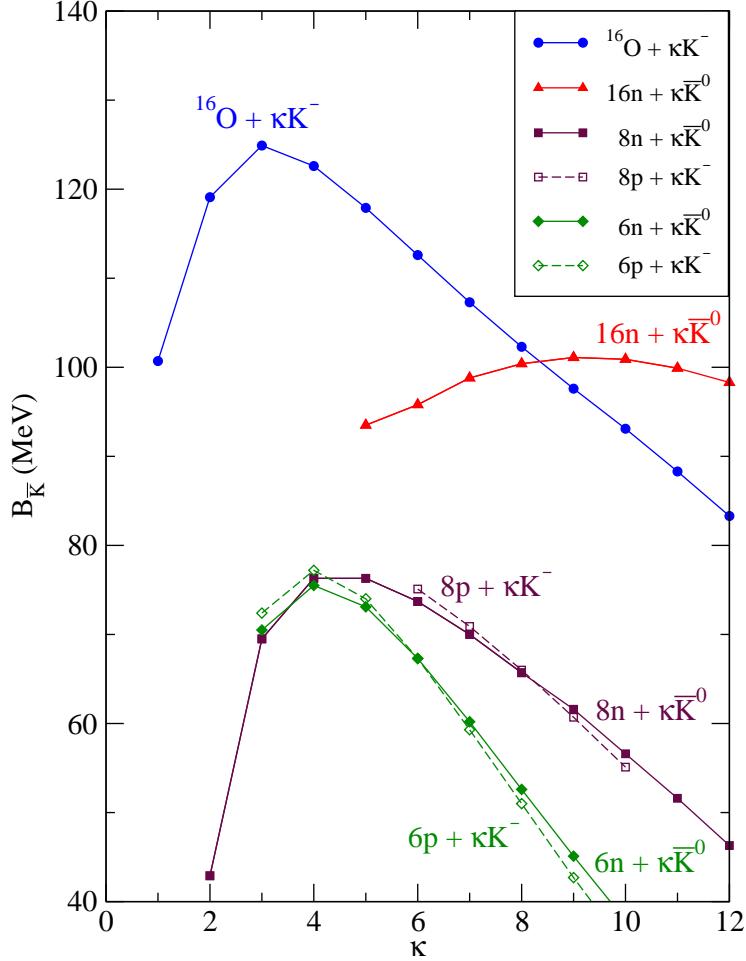


Fig. 2. 1s  $\bar{K}$  separation energy  $B_{\bar{K}}$  in multi- $\bar{K}$  nuclear systems, as a function of the number of  $\bar{K}$  mesons  $\kappa$ , calculated in the NL-SH RMF model [70], with  $\bar{K}$  vector coupling constants corresponding to the Tomozawa-Weinberg lowest order chiral Lagrangian [8,9] augmented by a  $\bar{K}$  scalar coupling designed to yield  $B_{\bar{K}} = 100$  MeV for  $^{16}\text{O} + 1\text{K}^-$ . I thank Daniel Gazda and Jiří Mareš for providing this figure.

teractions (each with equally mixed  $I = 0$  and  $I = 1$  components) provide considerably more attraction than the purely  $I = 1$   $K^-n$  and  $\bar{K}^0p$  interactions which also contribute in nuclear matter. Recent RMF calculations by Gazda et al. [69] demonstrate that a finite number of neutrons (protons) can be made self-bound by adding together a few  $\bar{K}^0$  ( $K^-$ ) mesons, with  $\bar{K}$  separation energies reaching values  $B_{\bar{K}} \sim 50 - 100$  MeV. This is shown in Fig. 2, where  $B_{\bar{K}}$  is plotted as a function of the number of  $\bar{K}$  mesons,  $\kappa$ , for systems of six, eight and sixteen neutrons. Shown also are the charge symmetric systems of six and eight protons. These systems are particle stable when  $\bar{K}$  charge exchange, strangeness exchange and multinucleon absorption channels are switched off, as practised in this particular calculation. For comparison,  $B_{K^-}$  values for multi- $K^-$  nuclei based on  $^{16}\text{O}$  are also shown in the figure. The ‘exotic’ stable neutron configurations are more tightly bound than in the corresponding ordinary nuclei with  $N \approx Z$  along the stability valley, and the

neutron single-particle spectra display substantial rearrangement [69]. However, the total binding energy of these exotic systems, with  $\bar{K}$  mesons, is lower than that of commensurate ordinary nuclei with  $\bar{K}$  mesons, so that the exotic systems are unstable against decay to ordinary nuclei by multiple charge-exchange  $\bar{K}^0 + n \rightarrow K^- + p$  reactions.

The various curves in Fig. 2 show a rise of  $B_{\bar{K}}$  with  $\kappa$ , reaching a maximum value and then decreasing steadily with  $\kappa$ . This decrease, due to the enhanced role of vector-meson repulsion among  $\bar{K}$  mesons upon increasing  $\kappa$ , persists in a robust way within various mean field models and over a broad range of coupling-constant values. The maximum values of  $B_{\bar{K}}$  do not exceed the range of values 100-200 MeV considered normally as providing deep binding for one antikaon. This range of binding energies leaves antikaons in multi- $\bar{K}$  nuclei comfortably above the range of energies where hyperons are relevant. It is unlikely therefore that multi- $\bar{K}$  nuclei may offer precursor phenomena in nuclei, under laboratory conditions, towards kaon condensation. Kaon condensation, however, is not ruled out in neutron stars, where time scales of the weak interactions are operative, allowing for example a rare weak decay such as  $e^- \rightarrow K^- + \nu_e$  to transform ‘dense’ electrons into antikaons, once the effective mass of  $K^-$  mesons drops below 200 MeV approximately.

## 6 Concluding remarks

Dalitz’s lifelong study of hypernuclei was central to his career as a phenomenologically inclined theoretical physicist. His style was unique. Asked by his then student Chris Llewellyn-Smith about ‘new theories’, Dalitz responded

- *My job is not to make theories - it’s to understand the data,*

*he saw the theorist’s role as being to find a way of representing experimental data so that they directly reveal nature’s secrets, as the Dalitz Plot had done [71].* His lifelong nourishment of hypernuclei has shaped and outlined for the last 50 years a field that is now maturing into a broader context of Strangeness Nuclear Physics. His wise and critical business-like attitude will be missed as new experimental facilities are inaugurated with the promise of discovering new facets of this field.

## References

- [1] I.J.R. Aitchison, F.E. Close, A. Gal, D.J. Millener, Nucl. Phys. A **771** (2006) 8.

- [2] M. Danysz, J. Pniewski, Phil. Mag. **44** (1953) 348.
- [3] R.H. Dalitz, Rev. Mod. Phys. **33** (1961) 471.
- [4] R.H. Dalitz, Annu. Rev. Nucl. Sci. **13** (1963) 339.
- [5] R.H. Dalitz, S.F. Tuan, Phys. Rev. Lett. **2** (1959) 425.
- [6] M. Alston, et al., Phys. Rev. Lett. **6** (1961) 698.
- [7] R.H. Dalitz, T.C. Wong, G. Rajasekaran, Phys. Rev. **153** (1967) 1617.
- [8] Y. Tomozawa, Nuovo Cimento A **46** (1966) 707.
- [9] S. Weinberg, Phys. Rev. Lett. **17** (1966) 616.
- [10] L. Castillejo, R.H. Dalitz, F.J. Dyson, Phys. Rev. **101** (1956) 453.
- [11] R.H. Dalitz, Strange particle theory in the cosmic-ray period, in *Proc. Colloque Int. sur l'Histoire de la Physique des Particules, Paris 1982*, J. Physique **43**, Colloq. C8 Suppl. (1982) pp. 195-205, and comments made on p. 406.
- [12] M. O'Byrne, From 'tau' to 'top' - the man behind the Dalitz plot, CERN COURIER **44**, issue 2 (2004) article 19.
- [13] R.H. Dalitz, Nucl. Phys. A **754** (2005) 14c.
- [14] R.H. Dalitz, Phys. Rev. **99** (1955) 1475.
- [15] B.W. Downs, R.H. Dalitz, Phys. Rev. **114** (1959) 593.
- [16] R.H. Dalitz, R.C. Herndon, Y.C. Tang, Nucl. Phys. B **47** (1972) 109.
- [17] R.H. Dalitz, Nature of the  $\Lambda^0 - N$  force from binding energies of light hyperfragments, in *Proc. 6th Annual Rochester Conference on High Energy Nuclear Physics, Rochester 1956*, Eds. J. Ballam, et al. (Interscience, New York, 1956) pp. V 40-43.
- [18] R.H. Dalitz, L. Liu, Phys. Rev. **116** (1959) 1312.
- [19] R. Ammar, R. Levi Setti, W. Slater, S. Limentani, P. Schlein, P. Steinberg, Nuovo Cimento **19** (1961) 20.
- [20] R. Ammar, W. Dunn, M. Holland, Nuovo Cimento **26** (1962) 840.
- [21] M.M. Block, R.H. Dalitz, Phys. Rev. Lett. **11** (1963) 96.
- [22] R.H. Dalitz, R. Levi Setti, Nuovo Cimento **30** (1963) 489.
- [23] A. Gal, J.M. Soper, R.H. Dalitz, Ann. Phys. **63** (1971) 53; **72** (1972) 445; **113** (1978) 79.
- [24] R.H. Dalitz, A. Gal, Ann. Phys. **116** (1978) 167.
- [25] D.J. Millener, A. Gal, C.B. Dover, R.H. Dalitz, Phys. Rev. C **31** (1985) 499.
- [26] O. Hashimoto, H. Tamura, Prog. Part. Nucl. Phys. **57** (2006) 564.

- [27] D.H. Davis, J. Sacton, Hypernuclear physics using photographic emulsion, in *Proc. Int. Conf. Hypernuclear Physics, ANL 1969*, Eds. A.R. Bodmer, L.G. Hyman (ANL, Argonne IL, 1969) pp. 159-192.
- [28] G. Bohm, et al., Nucl. Phys. B **24** (1970) 248; M. Jurić, et al., Nucl. Phys. B **47** (1972) 36.
- [29] R.H. Dalitz, D.H. Davis, D.N. Tovee, Nucl. Phys. A **450** (1986) 311c.
- [30] C.B. Dover, A. Gal, G.E. Walker, R.H. Dalitz, Phys. Lett. B **89** (1979) 26.
- [31] R.H. Dalitz, A. Gal, Phys. Lett. B **64** (1976) 154.
- [32] R.H. Dalitz, The present problems and future outlook in  $\Lambda$ -hypernuclear physics, in *Proc. Int. Conf. Hypernuclear Physics, ANL 1969*, Eds. A.R. Bodmer, L.G. Hyman (ANL, Argonne IL, 1969) pp. 708-747.
- [33] A.K. Kerman, H.J. Lipkin, Ann. Phys. **66** (1971) 738.
- [34] R.H. Dalitz, A. Gal, Phys. Rev. Lett. **36** (1976) 362.
- [35] E.H. Auerbach, A.J. Baltz, C.B. Dover, A. Gal, S.H. Kahana, L. Ludeking, D.J. Millener, Phys. Rev. Lett. **47** (1981) 1110; Ann. Phys. **148** (1983) 381.
- [36] R.H. Dalitz, Phys. Lett. **5** (1963) 53.
- [37] M. Danysz, et al., Phys. Rev. Lett. **11** (1963) 29; Nucl. Phys. **49** (1963) 121.
- [38] R.H. Dalitz, G. Rajasekaran, Nucl. Phys. **50** (1964) 450.
- [39] R.H. Dalitz, D.H. Davis, P.H. Fowler, A. Montwill, J. Pniewski, J.A. Zakrzewski, Proc. Royal Soc. A **426** (1989) 1.
- [40] A. Gal, C.B. Dover, Phys. Rev. Lett. **44** (1980) 379.
- [41] R.H. Dalitz, Nature **285** (1980) 11.
- [42] R.S. Hayano, et al., Nuovo Cimento A **102** (1989) 437.
- [43] R.H. Dalitz, D.H. Davis, A. Deloff, Phys. Lett. B **236** (1990) 76.
- [44] R.H. Dalitz, A. Deloff, Nucl. Phys. A **547** (1992) 181c.
- [45] R.H. Dalitz, A. Deloff, Nucl. Phys. A **585** (1995) 303c.
- [46] T. Nagae, et al., Phys. Rev. Lett. **80** (1998) 1605.
- [47] T. Harada, Phys. Rev. Lett. **81** (1998) 5287.
- [48] R.H. Dalitz, Nucl. Phys. A **691** (2001) 1c.
- [49] G.L. Shaw, M. Shin, R.H. Dalitz, M. Desai, Nature **337** (1989) 436.
- [50] Y. Akaishi, T. Yamazaki, Phys. Rev. C **65** (2002) 044005.
- [51] D.H. Davis, Nucl. Phys. A **754** (2005) 3c.

- [52] A. Gal, in preparation.
- [53] M. Sato, et al., Phys. Lett. B **659** (2008) 107.
- [54] T. Kishimoto, et al., Prog. Theor. Phys. **118** (2007) 181.
- [55] J. Yamagata, H. Nagahiro, S. Hirenzaki, Phys. Rev. C **74** (2006) 014604.
- [56] P. Kienle, in *Hypernuclear and Strange Particle Physics*, Proc. HYP06, Eds. J. Pochodzalla, Th. Walcher (SIF and Springer-Verlag, Berlin Heidelberg, 2007) pp. 225-229; Nucl. Phys. A **804** (2008) 286.
- [57] M. Agnello, et al., Phys. Rev. Lett. **94** (2005) 212303.
- [58] T.H. Tan, Phys. Rev. Lett. **23** (1969) 395.
- [59] C. Pigot, et al., Nucl. Phys. B **249** (1985) 172.
- [60] R.H. Dalitz, C.R. Hemming, E.J. Morris, Nukleonika **25** (1980) 1555; R.H. Dalitz, A. Deloff, Czech J. Phys. B **32** (1982) 1021; R.H. Dalitz, A. Deloff, Australian J. Phys. **36** (1983) 617.
- [61] M. Torres, R.H. Dalitz, A. Deloff, Phys. Lett. B **174** (1986) 213.
- [62] G. Toker, A. Gal, J.M. Eisenberg, Phys. Lett. B **88** (1979) 235; G. Toker, A. Gal, J.M. Eisenberg, Nucl. Phys. A **362** (1981) 405.
- [63] G. Coremans, et al., Nucl. Phys. B **16** (1970) 209.
- [64] G. Keyes, J. Sacton, J.H. Wickens, M.M. Block, Nuovo Cimento A **31** (1976) 401.
- [65] T. Yamazaki, Y. Akaishi, Phys. Lett. B **535** (2002) 70.
- [66] A. Doté, T. Hyodo, W. Weise, Nucl. Phys. A **804** (2008) 197.
- [67] N.V. Shevchenko, A. Gal, J. Mareš, Phys. Rev. Lett. **98** (2007) 082301; N.V. Shevchenko, A. Gal, J. Mareš, J. Révai, Phys. Rev. C **76** (2007) 044004.
- [68] Y. Ikeda, T. Sato, Phys. Rev. C **76** (2007) 035203.
- [69] D. Gazda, E. Friedman, A. Gal, J. Mareš, Phys. Rev. C **77** (2008) 045206.
- [70] M.M. Sharma, M.A. Nagarajan, P. Ring, Phys. Lett. B **312** (1993) 377.
- [71] C.H. Llewellyn-Smith, remarks made at the Dalitz memorial meeting (<http://www-thphys.physics.ox.ac.uk/user/SubirSarkar/dalitzmeeting/>) University of Oxford, 3 June 2006.